The effect of ECRH on the electron velocity distribution function

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As magnetic-confinement fusion sets its sights on the goal of partial or total reaction self-sustainment - a key step towards concrete energy generation - the function of external power sources shifts from bulk plasma heating to the sustainment of optimized plasma distribution functions. In particular, to the "tailoring" of favourable spatial profiles (of temperature, current, density etc.), is gradually being added the task of momentum-space "engineering". Indeed, in any driven system, breaking the tight bonds of thermodynamic equilibrium opens the possibility of population inversion - a stable non-equilibrium state with optimal properties for a specific goal: in this case, efficient fusion reactivity. Electromagnetic waves are an especially effective tool to this end, as lower-hybrid current-drive experiments proved well over twenty years ago. More recently, progress in high-power millimiter-wave generation has brought the technique of electron-cyclotron resonance heating (ECRH) to the fore, its short wavelength and unexcelled localization properties affording an unprecedented degree of phase-space manipulation.

The sustainment of fully non-inductive electron internal transport barriers is an emblematic recent example, combining velocity-space control (by Fisch-Boozer current drive) with real-space control (by safety-factor profile inversion) to enhance the fusion performance. The excitation of a non-Maxwellian electron population of a given energy, through surgical targeting of a unique physical/velocity-space resonance - by vertical launching in a tokamak - is another remarkable example of population inversion. While the flexibility and accuracy of ECRH make it a powerful tool, the ultimate limit to its efficacy is set by plasma self-organization: with very high-power ECRH, for instance, the maximum achievable distortion of the distribution function appears to be regulated by the cross-field transport of suprathermal electrons, which is enhanced by their long lifetime and driven by turbulence, intensified in turn by the high power input itself.

This paper will discuss the effect of ECRH on the electron distribution function in tokamaks, while focusing especially on the TCV device, whose very high power density has enabled particularly stringent tests of the potential of ECRH as a phase-space control tool. Special emphasis will be placed on the role played by diagnostics, such as electron-cyclotron and hard-X-ray emission detectors, and numerical codes exploring the linear and quasilinear stages of wave-particle interaction, in advancing our understanding of the underlying physics mechanisms.